A Thesis for the Degree of Master of Science

Characterization of Korean sweet potato starches: physicochemical, pasting, and digestion properties

한국산 11 품종 고구마 전분의 이화학 · 호화 및 소화 특성 연구

February, 2013

Baek, Hye Rim

Interdisciplinary Program for
Agricultural Biotechnology Graduate School
Seoul National University

농학석사학위논문

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백 혜 림

백 혜 림의 석사학위 논문을 인준함

2013년 2월

위 원 장 ___유 상 렬___ 인

부위원장 ___문 태 화___ 인

위 원 ___이 기 원___ 인

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Characterization of Korean sweet potato starches: physicochemical, pasting, and digestion properties

by

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Submitted in Partial Fulfillment of the Requirement for the Degree of Master of Science

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ABSTRACT

Physicochemical, pasting, and digestion properties of Korean sweet potato starches were investigated. Sweet potato starch granules were oval, round, polygonal, spherical, and bell-shaped and of 10.2-15.3㎛ in mean particle diameter. The average particle size of Jeongmi was the highest, while Daeyumi was the lowest. Amylose content of the sweet potato starches varied from 12.3 to 17.4%. Jeongmi showed the highest values for Mw (14.6×10^7g/mol), whereas Daeyumi had the lowest (7.2×10^7g/mol). A similar chain length distribution of amylopectin was found in 11 sweet potato starches. The portion of B_3 (DP≥37) correlated (r=0.66, p<0.01) with the amount of leached amylose. Thermal properties of DSC showed the high values of T_o, T_p, and T_c in Shinyulmi and Jeongmi, but a relatively low value in Daeyumi. All sweet potato starches exhibited a characteristic C_a-type diffraction pattern. Different patterns were revealed among the swelling factors of sweet potato starches depending on temperature. The contents of rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) in sweet potato starches ranged from 9.6 to 17.4%, 31.4 to 45.6%, 35.7 to 62.8%, respectively. Shinyulmi and Happymi had the highest SDS, and Jeongmi had the highest RS. According to the Rapid visco analyzer (RVA) viscosity profiles, differences were observed in pasting parameters such as pasting temperature, peak viscosity, final viscosity and breakdown. Happymi showed the highest breakdown, and lowest final viscosity, setback, pasting time, and pasting temperature.

Keywords: sweet potato starch, digestibility, slowly digestible starch, resistant starch, pasting properties

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INTRODUCTION

Sweet potato (*Ipomoea batatas* Lam) is one of the most important root crops in the world with more than 133 million tonnes produced worldwide annually (Waramboi et al., 2011). It is a staple food for globally millions of people and the seventh most abundant crop after wheat, rice, maize, potato, barley and cassava (Bovell-Benjamin, 2007). Furthermore, these days, its role has dramatically changed from a staple food to a health food. Sweet potato is used as powder, snack, sweet jelly, drink, starch, ethanol, food coloring, and so on (Palomar et al., 1981; Suzuki, 1978; Wanjekeche & Keya, 1995). Its starch is processed into an ingredient in bread, cakes, noodles and confectioneries. In recent years, new sweet potatoes have been developed by Bioenergy Crop Research Center, National Institute of Crop Science (NICS), Rural Development Administration (RDA) of Korean government for the purpose of producing colored sweet potato and high starch yield types.

At present time, especially colored sweet potato (orange, purple) is very popular in Korea due to its sweet taste, appearance, and flavor compared with normal, yellow-fleshed sweet potato. Although nutritional aspects of orange-fleshed sweet potato have been reported including β-carotene (Teow et al., 2007), physicochemical properties of its starch are rarely reported.

Starch has been known as the major storage polysaccharide of plants and is deposited in partially crystalline granules varying in morphology and molecular structure between and within plant species (Blazek and Copeland, 2008). Starch basically contains two types of biomacromolecules; amylose and amylopectin.

Nutritionally, starch is generally classified into rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) depending on the rate of digestion (Englyst et al., 1992). It has been shown that the RDS fraction compares well with glycemic index purported to increase the likelihood impact diabetes/pre-diabetes, cardiovascular disease indices, and obesity (Ludwig, 2000). SDS is the starch fraction which is digested completely, but its digestion rate is very slow compared to RDS. The physiological effects of SDS are useful in weight loss program for prolonged satiety and also helpful in diabetes. Moreover, SDS can provide a longer, more consistent source of systemic glucose (Lehmann and Robin, 2007). RS is , in general, clssasfied as dietary fiber and is fermented to produce a high level of butyrate that is beneficial to colonic health. Sajilata et al. (2006) stated that RS can prevent colonic cancer, have hypoglycemic and hypocholesterolemic effects, inhibit fat accumulation, and increase absorption of minerals. In the present study, the 13 sweet potato cultivars were grown in the same location and under the same environment conditions.

Thus, the variability among cultivars indicates genetic differences in sweet potato cultivars that affect physicochemical and digestion properties. Physicochemical and structural characteristics of starch vary among different varieties of the same botanical sources (Afoakwa, 2011).

With respect to Korean sweet potato, detailed studies on the physicochemical properties of either the starch or flour are conspicuously scarce. Moreover, there is a lack of adequate information on relationship between starch digestibility and its structural properties among different Korean sweet potato cultivars. Therefore, the aims of this study were to characterize the physicochemical, pasting, and digestion properties of sweet potato starches from 11 Korean cultivars in addition to Japanese Gold sweet potato and Pumpkin sweet potato; and to analyze the correlations among and between these properties.

MATERIALS AND METHODS

1. Materials

Korean native sweet potato cultivars, Gunmi, Gunpungmi, Daeyumi, Matnami, Borami, Shinyulmi, Jeonmi, Jeongmi, Hayanmi, Happymi, Heathymi, Pumpkin sweet potato, and Gold sweet potato were obtained from Mokpo Experiment Station, National Institute of Crop Science, Rural Development Administration of Korean government in Korea. Pancreatin (P-7545, activity 8×USP/g) was purchased from Sigma Chemical (St. Louis, MO, USA), amyloglucosidase (AMG 300L, activity 300 AGU/mL) from Novozymes (Bagsvaerd, Denmark), and isoamylase from Megazyme (Bray, Ireland).

2. Methods

2-1. Starch isolation

Sweet potatoes were washed and peeled. Immediately after peeling, they were sliced into 0.2mm thick pieces using a food slicer (Sungkwang Metal Co. Ltd., Seoul, Korea). Then, the sweet potatoes were soaked in distilled water and ground into small pieces using a blender (CR-481W, Samsung, Seoul, Korea). The pieces were passed through 100-mesh sieves, and the suspension was collected in a plastic container. After a solid layer of starch settled down, the supernatant was decanted, and the starch layer was dissolved in distilled water. This process was repeated until the supernatant became transparent. Finally, the suspended solution was centrifuged at 6,000 ×g for 15min. Then, the starch was dried at 40℃ in a drying oven and passed though a 100-mesh sieve.

2-2. Granular shape and size distribution

The granule morphology of sweet potato starches were observed using a CSB-HP3 light microscope (Samwon Scientific, Seoul, Korea) equipped with a polarizer. A small amount of starch was dispersed well in glycerol to prevent the movement of starch granules, and mounted onto a microscope slide with a cover slip. Images were captured using a digital camera (E8400, Nikon, Tokyo, Japan) and transferred to a computer. The particle size distribution of sweet potato starches was investigated using an Accusizer^{TM} 780 particle sizing & counting analyzer (Particle Sizing Systems, Port Richey, FL, USA)

2-3. Damaged starch content

Damaged starch contents of the isolated sweet potato starches were analyzed with a starch damage assay kit (Megazyme International Ireland Ltd.).

2-4. Amylose content

Absolute amylose contents of the sweet potato starches were determined with an amylose/amylopectin assay kit (Megazyme International Ireland Ltd.) based on the concanavalin A method (Gibson et al., 1997).

2-5. Branched chain length distribution

The amylopectin branched chain length distribution of starch sample was investigated after debranching the starch with isoamylase. Starch (15 mg) was dispersed in 90% DMSO (3 mL) and boiled for 15 min. To precipitate the starch, ethanol (15 mL) was added to starch suspension. The suspension was centrifuged at 10,000 ×g for 10 min twice. Distilled water (1.5 mL) was added to the precipitated starch and boiled for 10 min. After that, 1.5 mL of 50 mM sodium acetate buffer (pH 4.3) and 30 μL of isoamylase (Megazyme), which specifically hydrolyzes α-1,6-glycosidic linkages, were added to the suspension. The mixture was incubated in a water bath at 45°C and 50 rpm for 2 hr. After the reaction, samples were boiled for 10 min to stop enzyme reaction. Debranched samples were filtered through a 0.45-μm membrane filter and analyzed using high-performance size-exclusion chromatography on a Carbo-pack PA1 anion exchange column (250 × 4 mm; Dionex, Sunnyvale, CA, USA) with a pulsed amperometric detector (Dionex). After equilibrating the column with 150 mM NaOH, the sample was eluted with various gradients of 600 mM sodium acetate in 150 mM NaOH at a flow rate of 1 mL/min. The gradients of sodium acetate used were as follows: linear gradients from 0 to 20% for 0 to 5 min, from 20 to 45% for 6 to 30 min, from 46% to 55% for 31 to 60 min, from 56 to 60% for 61 to 80 min, from 61 to 65% for 81 to 90 min, from 66 to 80% for 91 to 95 min, and from 81 to 100% for 96 to 100 min. The values of the degree of polymerization (DP) from 1 to 7 were designated using a mixture of maltooligosaccharides (DP 1-7, Sigma Chemical).

2-6. Determination of molecular weight distribution by high-performance size-exclusion chromatography (HPSEC) – multi-angle laser-light scattering (MALLS) –refractive index (RI) system

Molecular masses of sweet potato starches were determined using HPSEC-MALLS-RI system. Starch (25 mg) was dispersed in 90% DMSO (5mL) and boiled for 15 min. The solution was mixed with ethanol (25mL) to precipitate starch and centrifuged at 10,000×g for 10 min. For washing, the pellet was dispersed in ethanol (30mL) again, and then centrifuged at

10,000×g for 10 min. This procedure was repeated three times. Then, the sample was dried completely by cold wind using a drier. Afterwards, 100 mM $NaNO_3$ (5mL) containing 0.02% NaN_3 was added to the pellet, and boiled for 15 min. This solution was autoclaved for 15 min and subsequently filtered through a 5.0 μm filter (Millipore) and injected into a HPSEC-MALLS-RI system.

The HPSEC-MALLS-RI system consisted of a model PU-2080 Plus (Jasco, Tokyo, Japan) with a 200 μL injector loop, a degasser (NO-OX Vacuum Station, Alltech, Deerfield, IL, USA), a differential refractive index detector (Opti-Lab, Wyatt Technology, Santa Barbara, CA, USA), and Shodex OH-Pak 804 and 806 columns (Showa Denko, Tokyo, Japan). Aqueous 100 mM $NaNO_3$ solution containing 0.02% NaN_3 was used as the mobile phase, and it was filtered through 0.22 μm filters (Millipore) and degassed before use. The flow rate was 0.4 mL/min and the experimental data collected from the DAWN DSP/OptiLab system were processed with ASTRA software (Version 4.09.07., Wyatt Technology).

2-7. X-ray diffraction patterns and relative crystallinity

X-ray diffraction analysis was performed using a powder X-ray diffractometer (Model New D8 advance, Bruker, Karlsruhe, Germany) analyzing at 40 kV and 40 mA. Starch sample scan was performed through

2θ range from 3° to 30° with a 0.02° step size and a count time of 2 sec. The area was calculated using the software developed by the instrument manufacturer (EVA, 2.0). The crystallinity was determined using the equation below.

$$\text{Relative crystallinity (\%)} = \left(\frac{\text{Area of the peaks}}{\text{Total curve area}}\right) \times 100$$

2-8. Measurement of thermal properties

The thermal properties of sweet potato starches were determined using a differential scanning calorimeter (Diamond DSC, Perking-Elmer Inc., Waltham, MA, USA). Starch (10 mg) was weighed in a hermetic aluminum pan (Seiko, Tokyo, Japan), and 40 μL of distilled water was added. The sample pans were sealed and kept at room temperature overnight for equilibrium. DSC scan was made as the sample was heated from 30 to 130°C at a scan rate of 5°C/min. As a reference, an empty pan was used.

2-9. Swelling factor

Swelling factor of starch was determined according to the method of Tester and Morrison (1990). Starch (100 mg) was suspended in 5 mL of distilled water and incubated in a water bath at 50, 60, 70, and 80°C for 30 min. After cooling the sample on ice, 0.5 mL of blue dextran solution (5 mg/mL) was added. The solution was centrifuged at 3,000 ×g for 15 min, and the absorbance of the supernatant was measured at 620 nm. Swelling factor (SF) was calculated as follows:

$$SF = 1 + \frac{7,700}{w} \times \frac{A_S - A_R}{A_S}$$

w : sample weight (mg)

A_s : absorbance of the supernatant

A_R : absorbance of reference (without starch)

2-10. Close packing and amylose leaching

Close packing (C*) and amylose leaching were determined by the method of Eerlingen (2007) with slight modification. Starch suspension (0.25% dry matter) was heated for 15 min in a water bath at 80°C. After cooling on ice for 5 min, the starch sample was centrifuged at 2,400 x g for 15 min. The supernatant was transferred to other tube with a pipette for the measurement of amylose content (Gilber and Spragg 1964). The sediment was weighed and close packing concentration (C*) was calculated as follows:

$$C^*(\%) = \frac{\text{starch weight (dry matter)} \times 100}{\text{sediment weight}}$$

For the determination of amylose content, supernatant (1.0 mL) was taken into a 50.0 mL tube. After adding 0.1 M NaOH (0.5 mL), the sample was boiled for 3 min and immediately cooled on ice. Following neutralization with 0.1 M HCl (0.5 mL), 20.0 mL of potassium hydrogen tartrate solution (5.0 g/L) and distilled water (27.5 mL) were added. Then, 0.5 mL of an iodine solution (200.0 mg I_2 and 2.0 g KI/100 mL) was added. After thorough mixing, the solution was placed at room temperature for 20 min. The absorbance of the solutions was measured at 680 nm. Pure potato amylose was used for the calibration curve.

2-11. Pasting properties

Pasting properties of starch suspensions were measured with a Rapid Visco Analyzer (RVA-4, Newport Scientific Pty, Ltd., Warriewood, Australia). Each potato starch (2g) was added to 25mL of distilled water. The starch suspension was equilibrated at 50°C for 1 min, heated from 50 to 95°C at a rate of 12°C/min, held at 95°C for 2.5 min, cooled to 50°C at the same rate, and held at 50°C for 2 min. The paddle speed was 960 rpm for the first 10 sec, then 160 rpm for the remainder of the experiment.

2-12. Starch digestibility

Starch digestibility was determined following the method of Brumovsky and Thompson (2001) with slight modification. To prepare enzyme solution, pancreatin (2g) was dissolved in 24 mL of distilled water and stirred for 10 min. It was centrifuged at 1,500 ×g for 10 min, and 20 mL of the supernatant was transferred into a beaker containing 3.6 mL of distilled water and 0.4 mL of amyloglucosidase. The enzyme solution was stored in a shaking incubator at 37°C for at least 10 min prior to use.

Each starch sample (30 mg) was weighed and placed in a 2 mL-microtube with a glass bead. After adding 0.75 mL of sodium acetate buffer (pH 5.2), the tube was stored in a shaking incubator at 37°C for 10 min. After storage, prepared enzyme solution (0.75 mL) was added to each tube and all samples were incubated in a shaking incubator with a shaking speed of 240 rpm at 37°C. The reaction was stopped at 10 min and 240 min by boiling for at least 10 min. The hydrolyzed glucose content in the supernatant obtained after centrifugation (5,000 ×g, 5 min) was measured using a GOP-POD kit (BCS Corp., Anyang, Korea).

Starch fractions were classified based on the rate of hydrolysis. Rapidly digestible starch (RDS) fraction was measured by the value of glucose after enzyme reaction for 10 min. Slowly digestible starch (SDS) fraction was defined as the amount digested between 10 min and 240 min of hydrolysis. The undigested fraction after 240 min was determined as resistant starch (RS) fraction.

2-13. Statistical analysis

Experiments were performed in triplicate, and mean values and standard deviations were reported except X-ray diffraction. Analysis of variance (ANOVA) was conducted and the mean separations done by the Duncan's multiple range text (p<0.05). All the statistical analyses described above were conducted using SPSS for Windows 12.0 software (SPSS Inc., Chicago, IL, USA). Pearson correlation coefficients (r) for the relationships between various starch properties were calculated.

RESULTS AND DISCUSSION

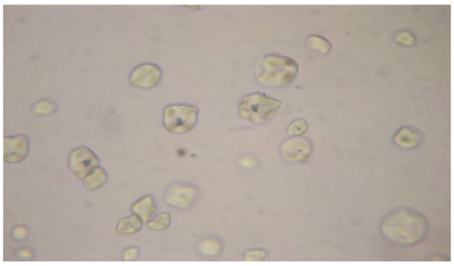
1. Morphological characteristics of sweet potato starch granules

The granular structure of sweet potato starch was studied using polarized light microscopy (Fig. 1). Under polarized light, the retention of granule crystallinity was observed by birefringence (Maltese cross). The birefringence of starch under polarized light indicates a radial orientation of the crystallites composed of polymer chains, such as amylose and amylopectin (Gallant et al., 1997).

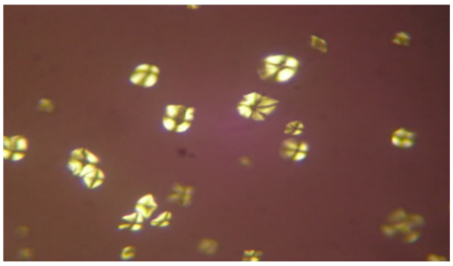
Starch granules from different botanical origins differ in morphology (Hoover, 2001). Especially, granules of tuber and root starches are oval, although round, spherical, polygonal, and irregular shaped granules also exist (Hoover, 2001). Light microscopy exhibited that all of the sweet potato starches had oval, round, spherical, polygonal, irregular, and bell-shaped granules and there was few pore on the surface of starch granules. Although various shapes of granules were observed in each sample, there were no clear differences in the granules from 13 types of sweet potato starches. Though some damaged granules, possibly from starch isolation, were observed, most granules were intact, with no obvious surface pores.

Sweet potato starch granules are similar in size to those of cassava and maize but are smaller than that of potato (Dreher and Berry, 1983). Particle size, including size distribution, is one of the characteristics that most markedly affect the functional properties of starch granules (Rasper, 1971). Starch composition, gelatinization and pasting properties, enzyme susceptibility, crystallinity, swelling, and solubility are all affected by granule size. According to Goering and Dehhas (1972), smaller granules have higher solubility and water absorption capacity than relatively large granules. Also, the smaller the particle size, the more digested was starch, presumably due to an increase in relative surface area (Mahasukhonthachat et al., 2010). Fig. 2 illustrates the size distributions of the native starch granules from different sweet potato cultivars. The sweet potato starches of different cultivars consisted of mixed populations of small and medium granules with a diameter range of 3.7-37.5 μm. Pumpkin sweet potato starch showed the widest granule distribution (3.7-35.5 μm), while Healthymi showed the narrowest range (5.1-22.4 μm). Sweet potato starch granules displayed average size from 10.2 to 15.3 μm. Among them, Jeongmi starch had the largest average granule diameter, followed by Gunmi starch. On the other hand, Borami had the smallest average granule diameter.

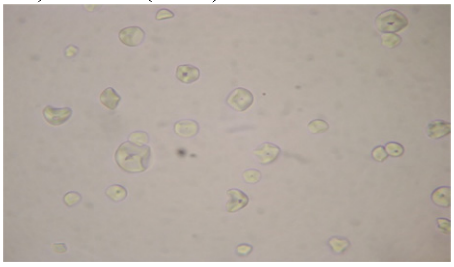
The variation in shape and size of starch granules may be due to the biological origin (Svegmark and Hermansson, 1993). The morphology of starch granules depends on the biochemistry of the amyloplast or chloroplast as well as physiology of the plant (Badenhuizen, 1969).



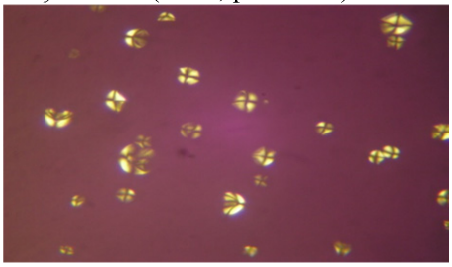
a-1) Gunmi (x 40)



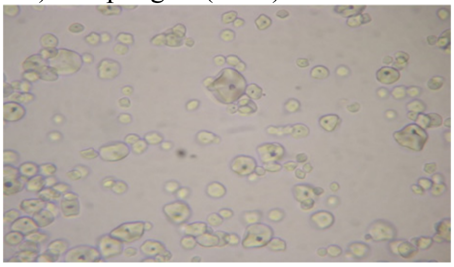
a-2) Gunmi (x 40, polarized)



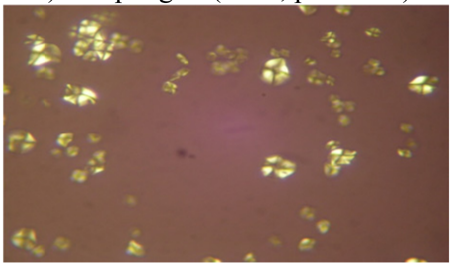
b-1) Gunpungmi (x 40)



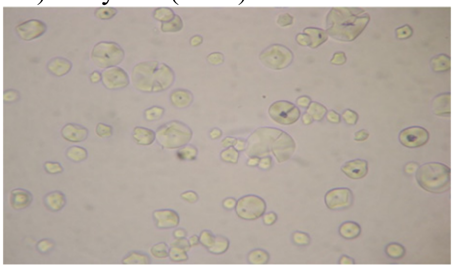
b-2) Gunpungmi (x 40, polarized)



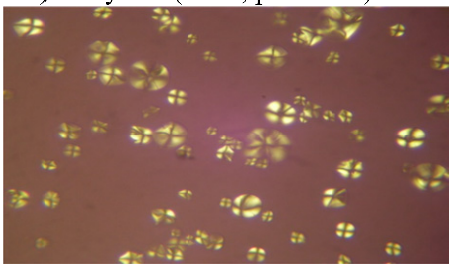
c-1) Daeyumi (x 40)



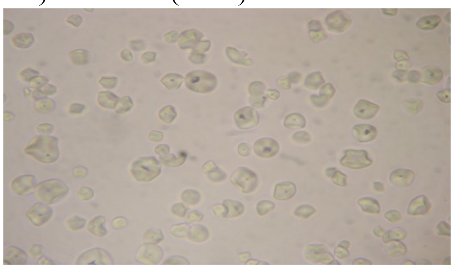
c-2) Daeyumi (x 40, polarized)



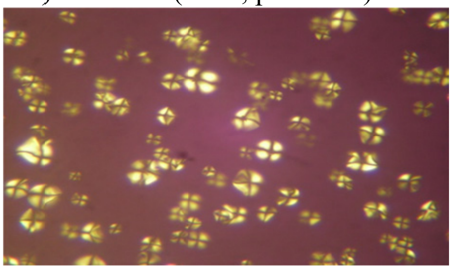
d-1) Matnami (x 40)



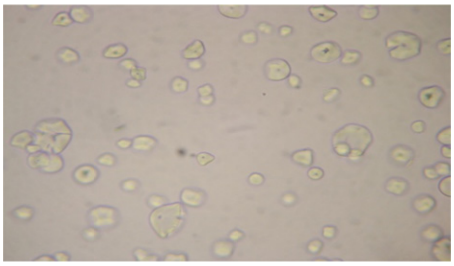
d-2) Matnami (x 40, polarized)



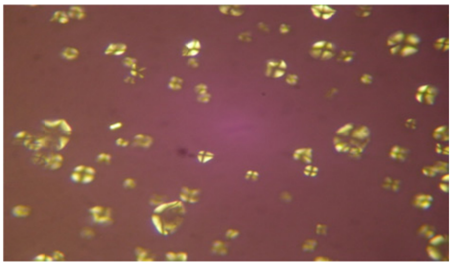
e-1) Borami (x 40)



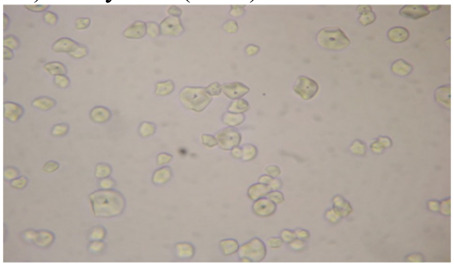
e-2) Borami (x 40, polarized)



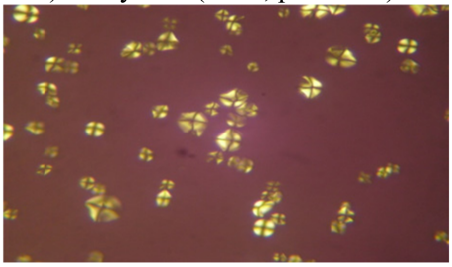
f-1) Shinyulmi (x 40)



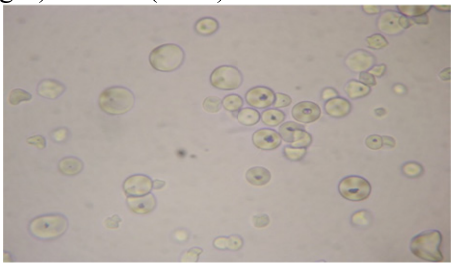
f-2) Shinyulmi (x 40, polarized)



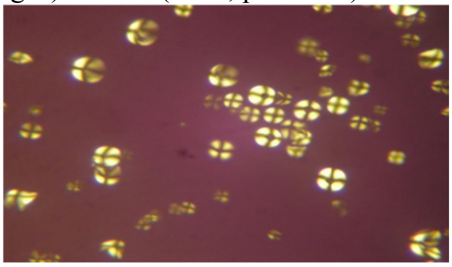
g-1) Jeonmi (x 40)



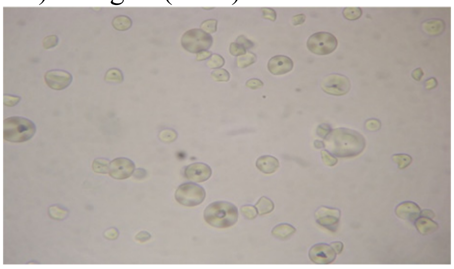
g-2) Jeonmi (x 40, polarized)



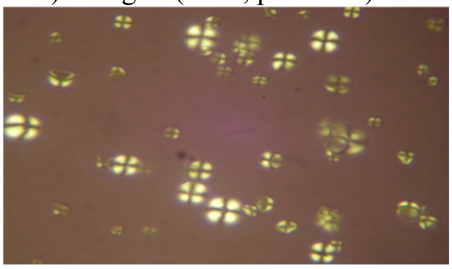
h-1) Jeongmi (x 40)



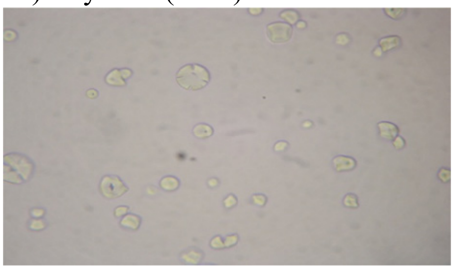
h-2) Jeongmi (x 40, polarized)



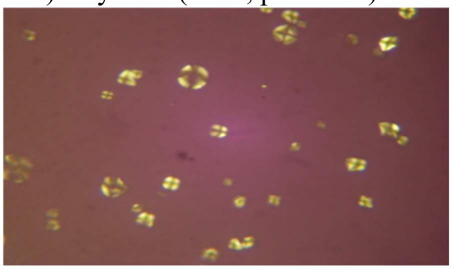
i-1) Hayanmi (x 40)



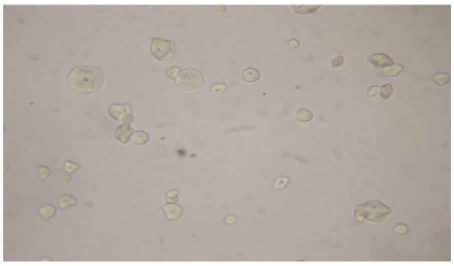
i-2) Hayanmi (x 40, polarized)

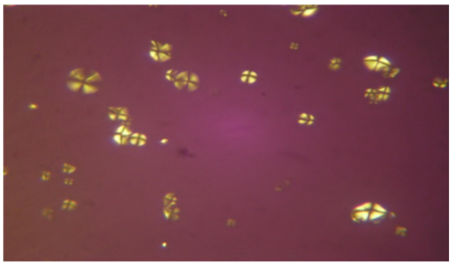


j-1) Happymi (x 40)

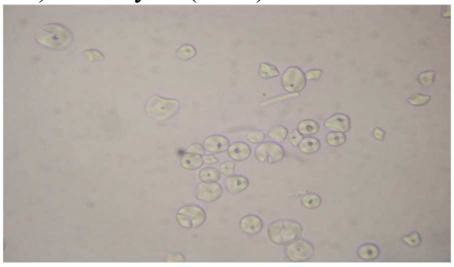


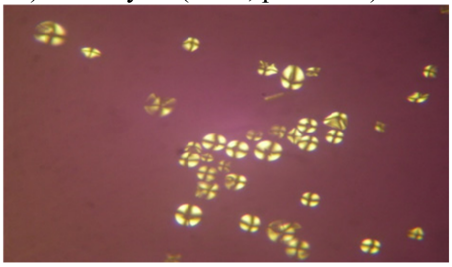
j-2) Happymi (x 40, polarized)



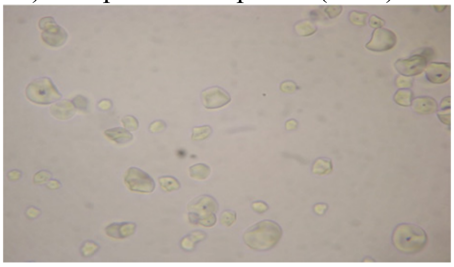


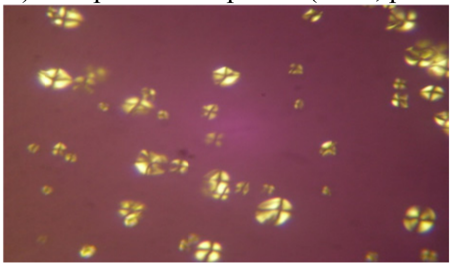
k-1) Healthymi (x 40)　k-2) Healthymi (x 40, polarized)





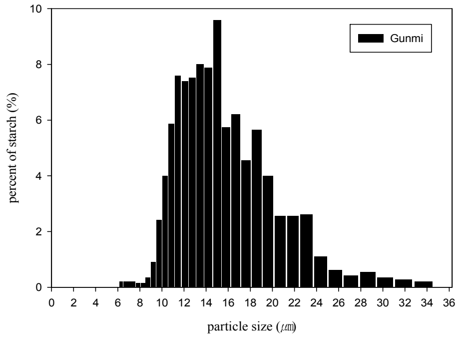
l-1) Pumpkin sweet potato (x 40)　l-2) Pumpkin sweet potato (x 40, polarized)

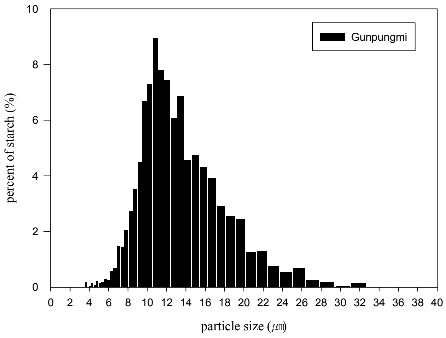


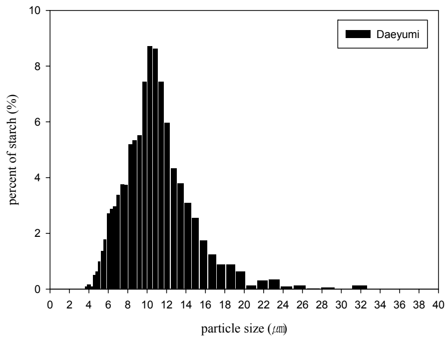


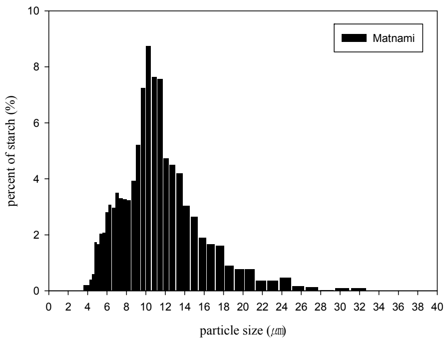
m-1) Gold sweet potato (x 40)　m-2) Gold sweet potato (x 40, polarized)

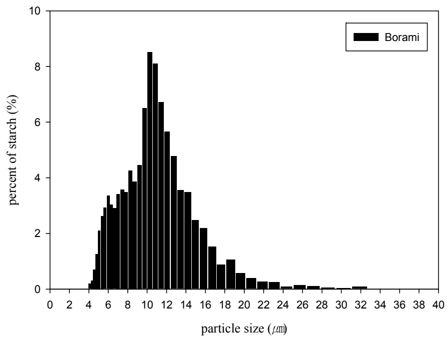
Fig. 1. Light micrographs of sweet potato starches

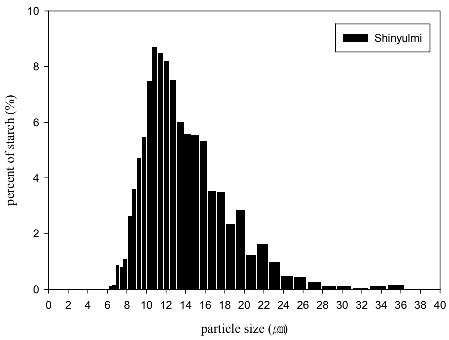

Gunmi
percent of starch (%)
particle size (㎛)

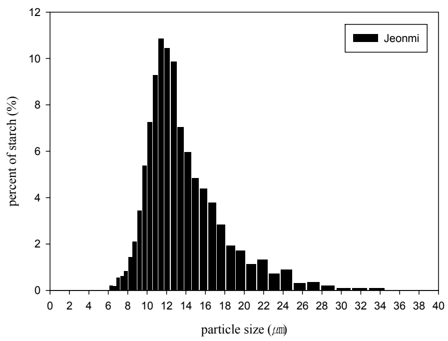

Gunpungmi
percent of starch (%)
particle size (㎛)

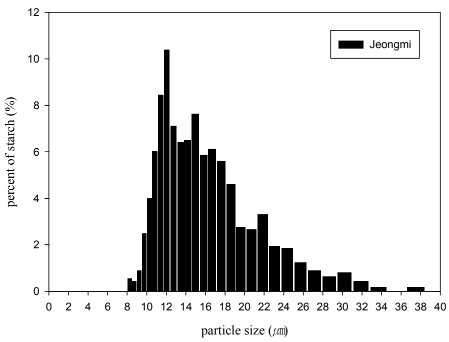

Daeyumi
percent of starch (%)
particle size (㎛)


Matnami
percent of starch (%)
particle size (㎛)


Borami
percent of starch (%)
particle size (㎛)


Shinyulmi
percent of starch (%)
particle size (㎛)


Jeonmi
percent of starch (%)
particle size (㎛)


Jeongmi
percent of starch (%)
particle size (㎛)

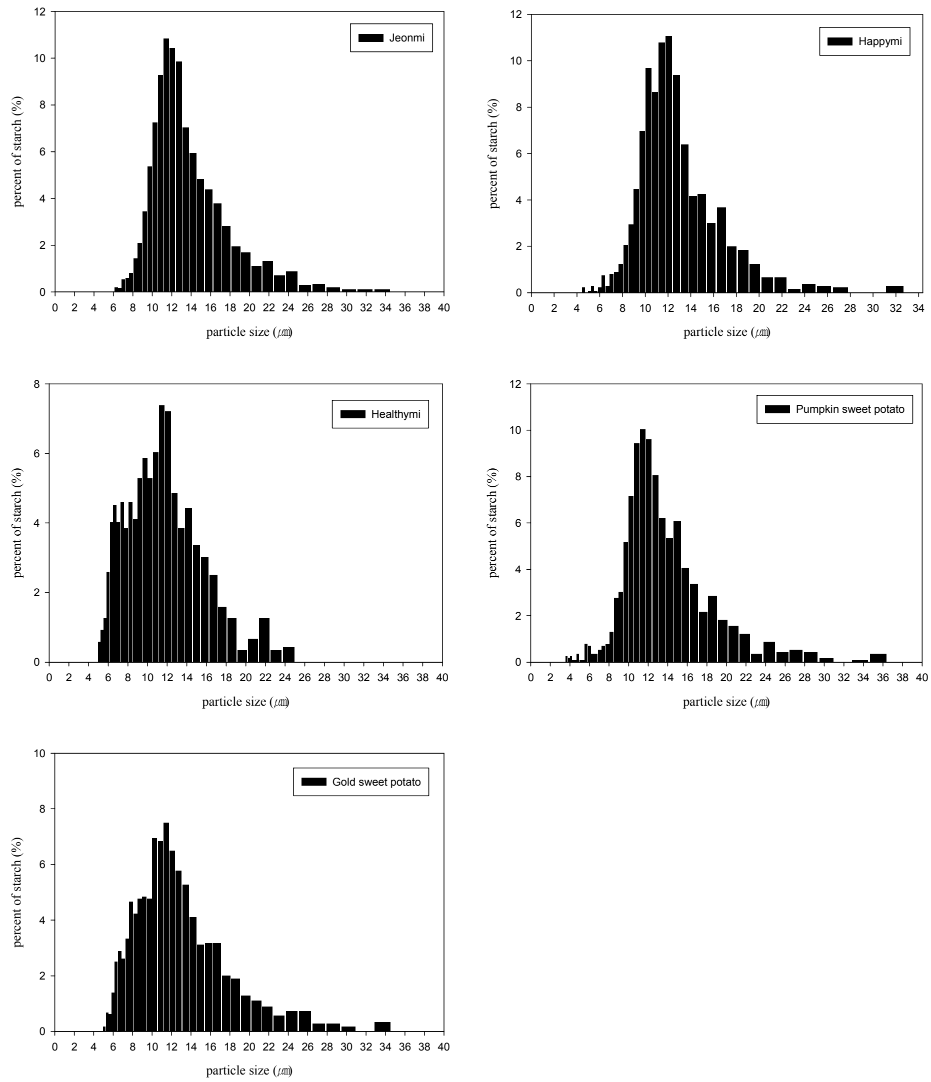


Fig. 2. Particle size distributions of sweet potato starches

Table 1. Granule size of the sweet potato starches determined by particle size distribution

Samples	Size range (μm)	Mean diameter (μm)	Mode (μm)	Average size (μm)
Gunmi	6.3 − 33.7	20.0	15.0	15.1^{b}
Gunpungmi	3.7 − 31.9	17.8	11.4	12.7^{cd}
Daeyumi	3.7 − 31.9	17.8	10.3	10.3^{e}
Matnami	3.7 − 31.9	17.8	10.3	10.5^{e}
Borami	4.1 − 31.9	18.9	10.3	10.2^{e}
Shinyulmi	6.3 − 35.5	20.9	10.8	13.1^{c}
Jeonmi	6.3 − 33.7	20.0	11.4	13.1^{c}
Jeongmi	8.3 − 37.5	22.9	12.1	15.3^{a}
Hayanmi	5.4 − 35.5	20.5	12.1	13.4^{c}
Happymi	4.6 − 31.9	18.2	12.1	12.3^{cd}
Healthymi	5.1 − 24.4	14.7	11.4	10.8^{e}
Pumpkin sweet potato	3.7 − 35.5	19.6	11.4	13.0^{c}
Gold sweet potato	5.1 − 33.7	19.3	11.4	11.7^{d}

2. Damaged starch

The content of damaged starch is an important quality index parameter in starchy food products. Excessive starch damage is detrimental, because it results in undesirable rheological-functional properties and unacceptable food (Evers and Stevens, 1985). Furthermore, damaged starch granules imbibe more water and are more susceptible to amylolysis. Granular integrity of starch can be affected by the mechanical action of the starch isolation process thus producing what is called damaged starch (Hoseney, 1994). Table 2 presents the contents of damaged starch of sweet potato starches. The damaged starch content of sweet potato starches was in the range of 0.5 to 2.9%. Although each sweet potato starch was produced by going through the isolation process, damaged starch content was rather small amount.

Table 2. Damaged starch content of sweet potato starches

Samples	Damaged starch (%)
Gunmi	0.6 ± 0.1^{gh}
Gunpungmi	1.4 ± 0.0^{c}
Daeyumi	2.9 ± 0.1^{a}
Matnami	1.3 ± 0.0^{cd}
Borami	0.9 ± 0.1^{f}
Shinyulmi	0.8 ± 0.1^{f}
Jeonmi	0.8 ± 0.1^{f}
Jeongmi	0.5 ± 0.1^{h}
Hayanmi	1.1 ± 0.1^{e}
Happymi	2.0 ± 0.1^{b}
Healthymi	1.2 ± 0.1^{de}
Pumpkin sweet potato	0.9 ± 0.1^{f}
Gold sweet potato	0.5 ± 0.4^{fg}

3. Amylose content

The amylose content of starch affects gelatinization and retrogradation properties, swelling power, and enzymatic susceptibility of starches (Gérard et al., 2001; Lindeboom et al., 2004). Therefore, it is important that the amylose content be quantified for food processing and product quality. There are some differences in the amylose content reported by different authors, which are related to the different analytical methods used and the age and variety of the plants. According to Shen and Sterling (1981), sweet potato starch has an amylose content of 13.4-22.5% depending on the variety, whereas values from 20 to 30% of amylose were reported by Waramboi et al. (2011). Starches that contain amylopectin with long branch chains cause overestimation of the amylose content when it is determined by the blue value method, because long chains of amylopectin also can form a helical complex with iodine. Therefore, absolute amylose contents of most of the starches studied were lower than their apparent amylose contents (Jane et al., 1999). In this study, the absolute amylose content of sweet potato starches ranged from 12.3 to 17.4%. Although there were no significant differences between amylose content of sweet potato starches, Jeonmi and Matnami showed the highest (17.4%) and lowest (12.3%) amylose content respectively.

Table 3. Amylose content of sweet potato starches

Samples	Amylose content (%)
Gunmi	16.7 ± 1.2^{ab}
Gunpungmi	14.9 ± 0.9^{c}
Daeyumi	14.6 ± 0.7^{c}
Mannami	12.3 ± 1.1^{d}
Borami	12.6 ± 0.2^{d}
Shinyulmi	15.8 ± 0.6^{abc}
Jeonmi	17.4 ± 0.5^{a}
Jeongmi	14.8 ± 1.0^{c}
Hayanmi	16.2 ± 1.3^{abc}
Happymi	15.1 ± 0.3^{c}
Healthymi	14.6 ± 1.0^{c}
Pumpkin sweet potato	16.8 ± 1.3^{ab}
Gold sweet potato	15.7 ± 0.5^{bc}

4. Branched chain length distribution of amylopectin and amylose leaching (AML)

One of the important properties of starch is its ability to swell and leach soluble materials while heated above its gelatinization temperature and this determines its specific functional property when utilized in food products (Noranizan et al., 2010). Starch swelling is viewed as a property of amylopectin (Gomand et al., 2010).

Table 4 represents the relative percent of total peak area with degree of polymerization (DP). Branch chain length distributions of all samples totally debranched by isoamylase were analyzed using HPASEC-PAD. Chain-length distributions were divided into four fractions as follows; A, B_1, B_2, and B_3 chains have the chain length of DP 6-12, 13-24, 25-26, and ≥37, respectively (Hanashiro et al., 1996).

At low temperatures, mainly amylose leaching occurs, while molecules of higher molecular weight leach at increasing heating temperatures (Eliasson and Gudmundsson, 1996; Tester and Morrison, 1990). Low values for amylose leaching (AML) indicate that only a fraction of amylose leaches out (Zobel, 1988).

In this study, the portion of B_3 (DP≥37) correlated ($r=0.66$, $p<0.01$) with the amount of leached amylose. Gunmi and Hayanmi had a large portion of B_3 (4.1%), and its amylose leaching content was somewhat high among the samples (6.5, and 6.2%, respectively). It was possibly due to the reason that amylopectin might be resistant to leaching when it had a high portion of long branch chain, and thus amylose could be relatively leached well.

The close packing concentration (C*) is the concentration where the swollen granules fill up the available space in the starch suspension. C* is an important parameter to understand starch behavior in applications and depends on temperature (Gomand et al., 2010).

Table 5 presents AML and C*of sweet potato starches. AML varied between 1.4 and 8.3 % in the sweet potato starches. Among them, AML of Jeongmi was the highest, and that of Borami and Healthymi was the lowest.

Table 4. Branched chain length distributions of sweet potato starches

Samples	Percent distribution (%)			
	DP 6-12	DP 13-24	DP 25-36	DP≥37
Gunmi	39.3 ± 0.3^{ef}	36.9 ± 0.6^{e}	10.1 ± 0.6^{a}	4.1 ± 0.1^{a}
Gunpungmi	41.8 ± 1.0^{b}	37.8 ± 0.1^{d}	10.0 ± 0.2^{a}	3.5 ± 0.2^{b}
Daeyumi	41.5 ± 0.5^{bc}	37.8 ± 0.1^{d}	9.2 ± 0.2^{d}	3.5 ± 0.2^{b}
Matnami	41.5 ± 0.2^{bc}	39.1 ± 0.2^{b}	9.4 ± 0.1^{cd}	2.9 ± 0.1^{cd}
Borami	40.1 ± 0.6^{de}	40.0 ± 0.4^{a}	9.6 ± 0.1^{bc}	3.0 ± 0.3^{c}
Shinyulmi	44.7 ± 0.3^{a}	35.9 ± 0.2^{f}	7.0 ± 0.2^{f}	2.9 ± 0.2^{cd}
Jeonmi	40.5 ± 0.5^{d}	39.0 ± 0.1^{b}	9.9 ± 0.1^{ab}	3.6 ± 0.1^{b}
Jeongmi	39.9 ± 0.3^{de}	40.4 ± 0.2^{a}	10.1 ± 0.2^{a}	3.8 ± 0.1^{b}
Hayanmi	38.8 ± 0.1^{f}	39.0 ± 0.2^{b}	10.1 ± 0.2^{a}	4.1 ± 0.1^{a}
Happymi	40.4 ± 0.2^{d}	40.1 ± 0.1^{a}	9.1 ± 0.2^{d}	2.3 ± 0.2^{e}
Healthymi	40.3 ± 0.6^{d}	40.2 ± 0.2^{a}	8.5 ± 0.1^{e}	2.7 ± 0.2^{d}
Pumpkin sweet potato	42.2 ± 0.2^{b}	37.5 ± 0.2^{d}	9.6 ± 0.1^{bc}	3.5 ± 0.2^{b}
Gold sweet potato	40.8 ± 0.7^{cd}	38.4 ± 0.1^{c}	10.2 ± 0.3^{a}	3.8 ± 0.3^{b}

Table 5. Amounts of amylose leaching (AML) and close packing concentrations (C^*) of sweet potato starches

Samples	AML (%)	C^* (%)
Gunmi	6.5 ± 0.4^{b}	3.7 ± 0.2^{fg}
Gunpungmi	6.0 ± 1.0^{bc}	4.4 ± 0.3^{bcd}
Daeyumi	6.2 ± 1.6^{bc}	4.7 ± 0.5^{b}
Matnami	3.7 ± 0.4^{d}	4.2 ± 0.0^{cde}
Borami	1.4 ± 0.6^{de}	4.8 ± 0.1^{b}
Shinyulmi	4.5 ± 0.6^{cd}	3.8 ± 0.4^{efg}
Jeonmi	4.9 ± 0.3^{bc}	4.0 ± 0.1^{efg}
Jeongmi	8.2 ± 1.1^{a}	3.5 ± 0.1^{g}
Hayanmi	6.2 ± 1.6^{bc}	4.8 ± 0.3^{b}
Happymi	3.7 ± 0.4^{d}	4.0 ± 0.1^{def}
Healthymi	1.4 ± 0.6^{de}	4.4 ± 0.2^{bcd}
Pumpkin sweet potato	4.5 ± 0.6^{c}	4.5 ± 0.1^{bc}
Gold sweet potato	3.9 ± 0.4^{d}	5.2 ± 0.1^{a}

5. Molecular weight distributions determined by HPSEC-MALLS-RI

Molecular characteristics of sweet potato starches were analyzed using absolute weight-average molecular weight and z-average radius of gyration (Rg). The structural data obtained by HPSEC-MALLS-RI system using DMSO as a dissolution solvent are shown in Table 6. Significant differences were observed in molecular weight of amylopectin among sweet potato starches. In this study, the number average molecular weight (Mn) and the weight average molecular weight (Mw) of sweet potato starches correlated with RS content (r=0.415, 0.577, $p<0.01$, respectively). Jeongmi had high Mw (14.6×10^7g/mol) and RS (62.8%) content, while Daeyumi had the lowest value of Mw (7.2×10^7g/mol) and RS (42.4%) among Korean sweet poato starches.

Jeongmi with the highest value of Mw of amylopectin showed a high Rg (223.4 nm), and Borami having the greatest Rg (291.6 nm) displayed a rather high Mw (13.3×10^7g/mol). Similar realationship between Mw of amylpectin and Rg has been reported earlier for pigeon pea and barely starches (Sandhu and Lim, 2008; You and Izydorczyk, 2002).

Interestingly, there was a negative correlation (r=-0.498, $p<0.01$) between Rg and amylose leaching. As Rg value indicates the volume occupied by the molecule in a solution, the branched chain-length and branching pattern of the amylopectin molecule are expected to affect the Rg in the solution (Yoo and Jane, 2002). Patindol et al. (2007) suggested that smaller Rg of amylopectin might be less capable of interacting with each other and amylose. Therefore, amylose could less likely leach out when amylopectin had a high Rg.

In general, polydispersity values (Mw/Mn) of sweet potato starches had the range from 1.2 to 1.8 except for Borami. Polydispersity of Borami was higher than 2, and it might be caused by other materials except starch. Lower polydispersity implies a more homogenous distribution of amylopectin molecules, while higher value means a more heterogenous distribution of amylopectin (Patindol et al., 2007).

Table 6. Molecular characteristics of sweet potato starches

Samples	Mn (x 10^7g/mol)	Mw (x 10^7g/mol)	Rg (Tsakama et al.)	Polydispersity (Mw/Mn)
Gunmi	6.6 ± 0.7^{cde}	9.4 ± 0.8^{defg}	206.7 ± 10.1^{cd}	1.4 ± 0.1^{de}
Gunpungmi	5.5 ± 0.3^{e}	8.0 ± 0.8^{fg}	192.8 ± 8.1^{de}	1.5 ± 0.1^{cde}
Daeyumi	5.7 ± 1.0^{e}	7.2 ± 1.8^{g}	169.5 ± 12.4^{e}	1.2 ± 0.1^{e}
Matnami	7.8 ± 0.4^{bcd}	12.6 ± 0.4^{abc}	236.2 ± 4.5^{bc}	1.6 ± 0.1^{bcd}
Borami	6.3 ± 1.1^{de}	13.3 ± 0.1^{ab}	291.6 ± 27.3^{a}	2.1 ± 0.1^{a}
Shinyulmi	8.1 ± 1.3^{abc}	10.8 ± 2.5^{bcd}	214.3 ± 27.1^{bcd}	1.3 ± 0.2^{de}
Jeonmi	9.6 ± 1.1^{a}	13.1 ± 1.5^{abc}	221.1 ± 9.2^{bcd}	1.4 ± 0.0^{de}
Jeongmi	8.1 ± 1.0^{abc}	14.6 ± 1.6^{a}	223.4 ± 16.6^{bcd}	1.8 ± 0.4^{b}
Hayanmi	5.6 ± 0.3^{e}	9.9 ± 1.4^{def}	213.3 ± 12.3^{bcd}	1.8 ± 0.2^{bc}
Happymi	7.3 ± 0.2^{bcd}	10.7 ± 1.3^{cde}	205.0 ± 24.5^{cd}	1.5 ± 0.2^{cde}
Healthymi	8.6 ± 0.9^{ab}	13.9 ± 1.6^{a}	233.3 ± 27.9^{bc}	1.6 ± 0.1^{bcd}
Pumpkin sweet potato	8.5 ± 0.9^{ab}	12.9 ± 0.2^{abc}	241.4 ± 27.9^{b}	1.5 ± 0.2^{cde}
Gold sweet potato	5.3 ± 0.9^{e}	8.3 ± 0.5^{efg}	218.5 ± 7.7^{bcd}	1.6 ± 0.2^{bcd}

6. X-ray diffraction pattern and crystallinity

The crystalline nature of a starch granule can be defined by the position of the X-ray diffraction peaks (Zobel, 2006). Hizukuri (1969) demonstrated that mixtures of A- and B- type starches produced an intermediate pattern, C-type. As expected, all sweet potato starches exhibited C-type diffraction pattern with three distinct intensities; 17.2°, 18.1° and 23.1° 2θ angles (Fig. 3). Not only Korean sweet potato cultivars but also Gold sweet potato and Pumpkin sweet potato starches showed the same X-ray diffraction. Hizukuri, subclassified C-type as C_a-, C_b-, and C_c-type on the basis of their resemblance to either A-type, B-type, or a type between A and B, respectively. A type pattern displays main peaks at 2θ = 15.0°, 17.0°, 17.9°, and 23° (Hanashiro et al., 1996). According to this, all sweet potato starches used in the current study were of C_a type. Despite the similarity in X-ray diffraction pattern, significant differences were observed in the relative crystallinity among sweet potato starches. The degree of relative crystallinity of Matnami was estimated to be 56.0% compared with 44.4% for Gold sweet potato starch.

Abdel-Aal et al. (2002) reported that relative crystallinity of starch could be influenced by amylopectin content. However, there were no significant differences between amylose contents of sweet potato starches, and relative crystallinity of sweet potato starches did not relate to amylopectin content.

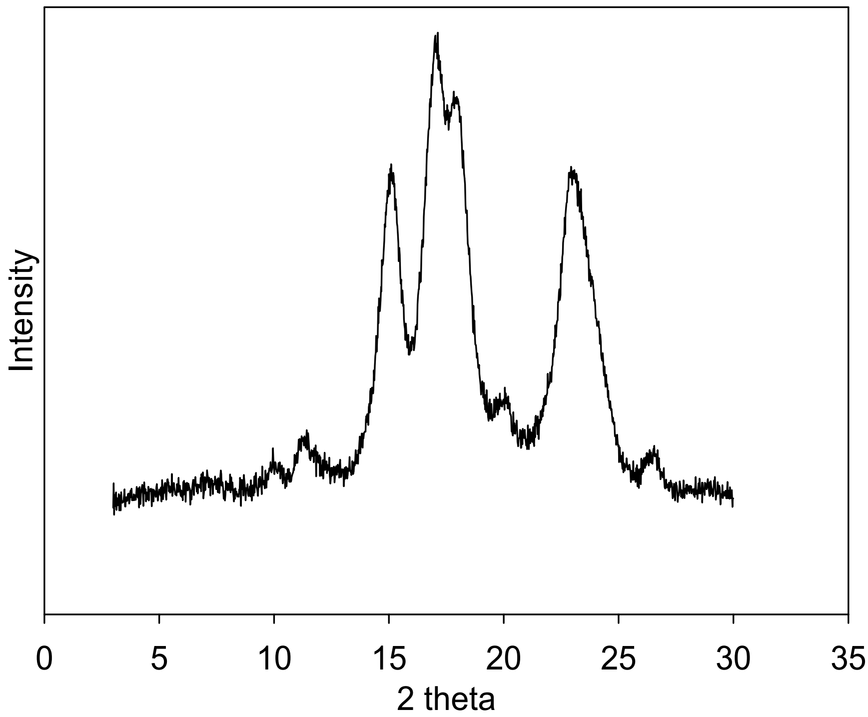


Fig. 3. X-ray diffractogram of sweet potato starch; Gunmi

It represents X-ray diffractograms of all sweet potato starches.

Table 7. Relative crystallinity of sweet potato starches

Samples	Relative crystallinity (%)
Gunmi	51.2
Gunpungmi	54.4
Daeyumi	53.0
Matnami	56.0
Borami	50.9
Shinyulmi	50.5
Jeonmi	52.3
Jeongmi	52.3
Hayanmi	49.7
Happymi	48.3
Healthymi	49.0
Pumpkin sweet potato	46.1
Gold sweet potato	44.4

7. Thermal properties

DSC was used to study starch gelatinization which involves disruption of the native structure of starch granules. Gelatinization is the loss of macromolecular organization within the starch granules in the presence of heat and water. The differences in gelatinization temperature can be attributed to the differences in size, form and distribution of starch fractions within the granule (Kaur et al., 2010).

The results of DSC analysis of the sweet potato starches are presented in Table 8. Shinyulmi and Jeongmi showed high T_o, T_p, and T_c, whereas the lowest values were observed for Gold sweet potato starch. Gelatinization temperatures can be affected by amylose content (Demeke et al., 1999; Jane et al., 1999; Stevenson et al., 2006). As mentioned in "Amylose content" section, amylose contents of 13 sweet potato starches were not significantly different, suggesting that the differences in gelatinization temperature among starches were not caused by different amylose content. Gelatinization occurs initially in the amorphous regions of the granule, because hydrogen bonding is weakened in these areas (Singh et al., 2003). It involves melting and uncoiling of the outer chains of amylopectin that are packed together as double helices in clusters (Sandhu and Lim, 2008). ΔH is mainly due to the melting of imperfect amylopectin-based crystals, with potential contributions from crystal-packing and helix-melting enthalpies (Lopez-Rubio et al., 2008). The lower transition temperatures and higher *ΔH* of Borami and Healthymi starches (22.7, and 19.9 J/g, respectively) suggested the disruption of double helices (in amorphous and crystalline regions) during gelatinization was more pronounced in other starches.

In addition, as discussed in detail later "Digestibility" section, gelatinization temperatures (T_o, T_p, and T_c) were shown to have positive correlations with SDS+RS (r=0.456, 0.562, and 0.565, respectively, $p<0.01$).

Table 8. Gelatinization parameters of sweet potato starches

Samples	T_o (°C)[1)]	T_p (°C)	T_c (°C)	T_c-T_o (°C)[2)]	*ΔH* (J/g)
Gunmi	64.8 ± 0.2^{d}	70.2 ± 0.1^{gh}	73.9 ± 0.4^{g}	9.1 ± 0.5^{g}	17.7 ± 1.8^{c}
Gunpungmi	66.9 ± 0.4^{bc}	71.8 ± 0.1^{ef}	76.8 ± 1.1^{e}	9.9 ± 0.7^{fg}	13.9 ± 1.5^{e}
Daeyumi	63.8 ± 0.1^{e}	71.7 ± 0.0^{f}	80.3 ± 0.0^{b}	16.4 ± 0.1^{a}	12.1 ± 0.2^{f}
Matnami	67.4 ± 0.5^{b}	73.0 ± 0.4^{bc}	78.6 ± 1.2^{d}	11.2 ± 1.4^{e}	15.2 ± 0.9^{d}
Borami	66.4 ± 0.0^{c}	72.7 ± 0.0^{cd}	76.5 ± 0.0^{e}	10.1 ± 0.0^{fg}	22.7 ± 0.2^{a}
Shinyulmi	70.6 ± 0.0^{a}	75.0 ± 0.0^{a}	80.0 ± 0.0^{bc}	9.4 ± 0.0^{g}	9.3 ± 0.1^{g}
Jeonmi	64.7 ± 0.1^{d}	72.6 ± 1.5^{cde}	79.4 ± 0.0^{cd}	14.7 ± 0.1^{b}	16.4 ± 0.0^{d}
Jeongmi	67.2 ± 0.0^{b}	73.6 ± 0.0^{b}	82.0 ± 0.0^{a}	14.7 ± 0.0^{b}	15.9 ± 0.1^{d}
Hayanmi	62.0 ± 0.5^{g}	69.8 ± 0.1^{h}	75.5 ± 0.4^{f}	13.5 ± 0.9^{c}	16.2 ± 0.2^{d}
Happymi	62.8 ± 0.1^{f}	70.4 ± 0.0^{gh}	75.3 ± 0.0^{f}	12.5 ± 0.1^{cd}	17.9 ± 0.2^{c}
Healthymi	64.6 ± 0.7^{d}	72.0 ± 0.1^{def}	76.9 ± 0.3^{e}	12.3 ± 0.7^{d}	19.9 ± 0.1^{b}
Pumpkin sweet potato	65.0 ± 0.0^{d}	70.8 ± 0.4^{g}	75.0 ± 0.5^{f}	10.1 ± 0.5^{fg}	17.8 ± 0.3^{c}
Gold sweet potato	62.3 ± 0.2^{g}	68.9 ± 0.3^{i}	73.0 ± 0.6^{g}	10.8 ± 0.8^{ef}	16.4 ± 0.9^{d}

1) T_o, T_p, and T_c indicate the onset, peak, and conclusion temperatures of gelatinization, respectively.
2) T_c-T_o denotes the temperature range of gelatinization. *ΔH* indicates the gelatinization enthalpy.

8. Swelling factor (SF)

The starch molecules are held together by hydrogen bonding in the form of crystalline bundles, which are called micelles (Oladebeye et al., 2009). The strength and character of the micelle network within the granule is the major factor controlling the swelling behavior of starch. Therefore, swelling power patterns of starches have been used to provide evidence for associative binding force within the granules (Leach et al., 1959).

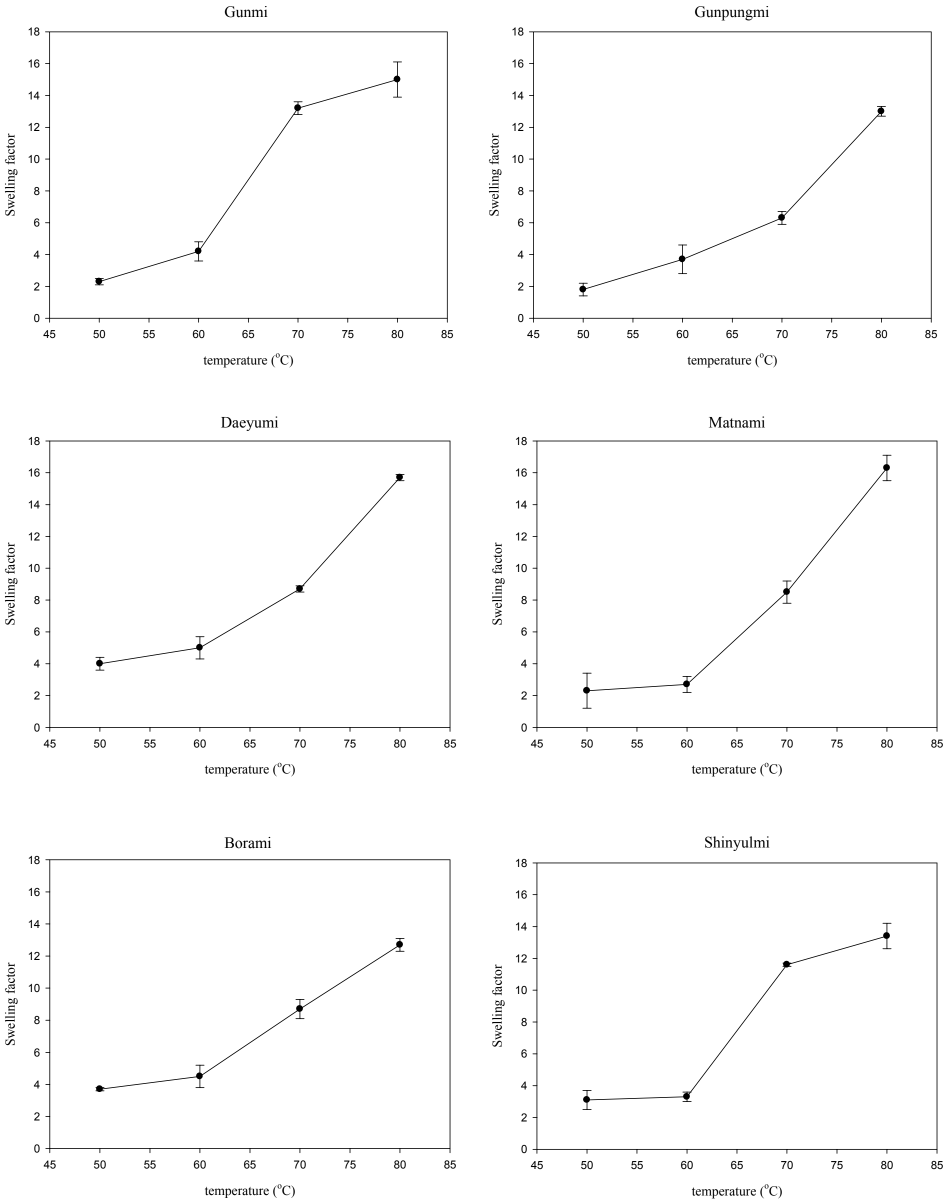
It has been reported that amylose acts both as diluent and inhibitor of swelling, especially in the presence of lipids which can form insoluble complexes with some of the amylose during swelling and gelatinization (Tester and Karkalas, 1996; Zeleznak and Hoseney, 1987). As expected, swelling factor for all sweet potato starches increased with increasing temperature. Swelling factor values rapidly increased at 60-70°C or 70-80°C depending on the sample. The swelling factor of Gunmi had a considerable change between 60°C and 70°C, whereas that of Daeyumi sharply increased between 70°C and 80°C. Interestingly, in case of Pumpkin sweet potato starch, it was shown that swelling at the temperature range of 50-60°C dramatically changed. The swelling factor at 80°C obtained in Hayanmi was the lowest, while the highest value was shown in case of Healthymi. These observed differences of swelling factor depending on the temperature and sample type were caused by many factors. Factors like amylose-amylopectin ratio, chain length and molecular weight distribution, degree/length of branching and conformation also decide the swelling and solubility (Moorthy, 1994). There is a possible relationship between swelling volumes and cooking quality (Moorthy, 1994).

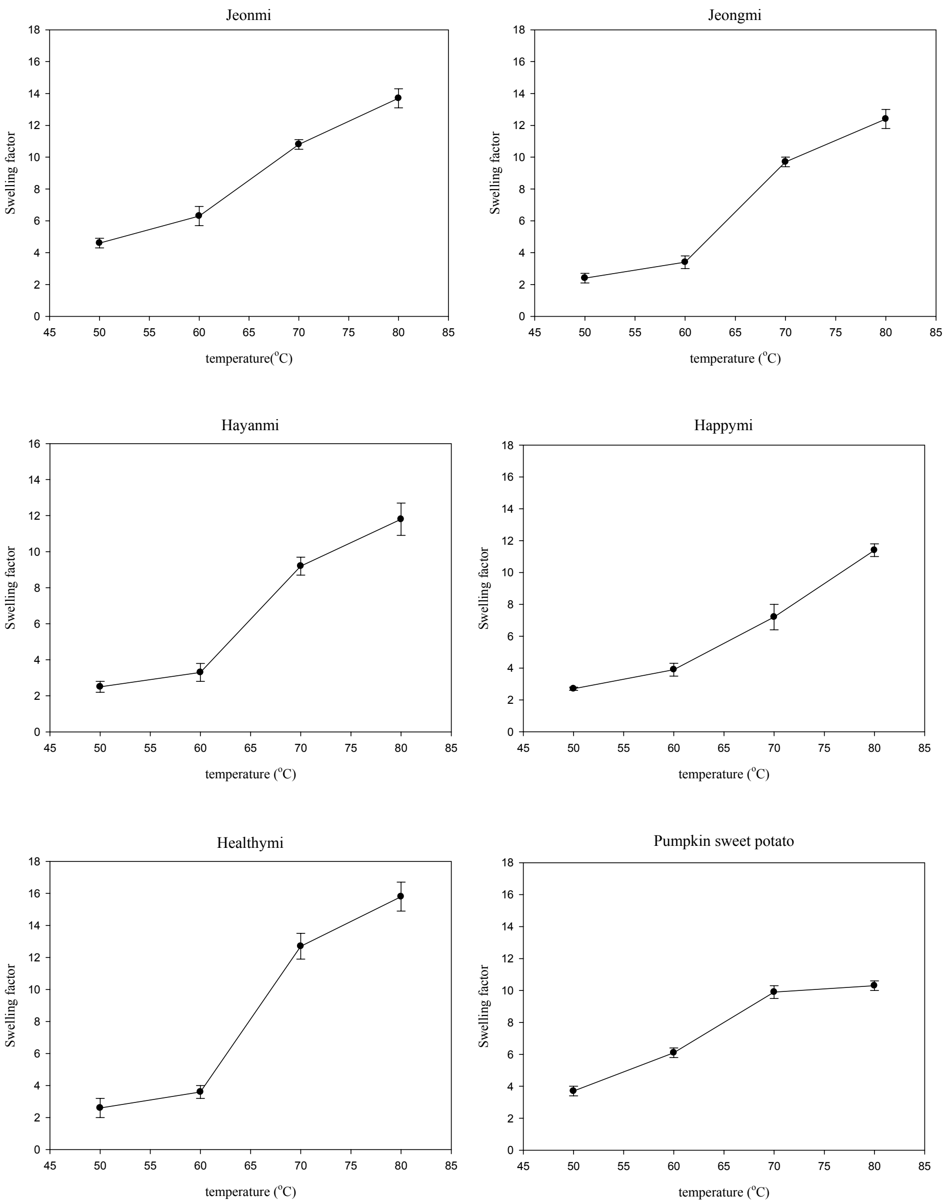
Srichuwong et al. (2005) mentioned that swelling ability contributes to important characteristics, such as pasting and rheological properties, of most starchy food products. The loss of free water and restricted flow of water due to enormously swollen granules occupying more space contribute to the increased viscosity of the starch heating system.

It is known that more highly swollen granules lead to a reduction in starch paste rigidity (Eliasson, 2007). Carnali and Zhou (1996) found that the rigidity of granules influences the rheology of pastes/gel in proportion to the temperature at which the starch has been pasted.

Table 9. Swelling factor of sweet potato starches

Samples	50°C	60°C	70°C	80°C
Gunmi	2.3 ± 0.2^{cd}	4.2 ± 0.6^{bc}	13.2 ± 0.4^{ab}	15.0 ± 1.1^{ab}
Gunpungmi	1.8 ± 0.4^{d}	3.7 ± 0.9^{cde}	6.3 ± 0.4^{g}	13.0 ± 0.3^{cd}
Daeyumi	4.0 ± 0.4^{ab}	5.0 ± 0.7^{b}	8.7 ± 0.2^{e}	15.7 ± 0.2^{a}
Matnami	2.3 ± 1.1^{cd}	2.7 ± 0.5^{e}	8.5 ± 0.7^{e}	16.3 ± 0.8^{a}
Borami	3.7 ± 0.1^{b}	4.5 ± 0.7^{bc}	8.7 ± 0.6^{e}	12.7 ± 0.4^{cde}
Shinyulmi	3.1 ± 0.6^{c}	3.3 ± 0.3^{de}	11.6 ± 0.1^{c}	13.4 ± 0.8^{cd}
Jeonmi	4.6 ± 0.3^{a}	6.3 ± 0.6^{a}	10.8 ± 0.3^{c}	13.7 ± 0.6^{bc}
Jeongmi	2.4 ± 0.3^{cd}	3.4 ± 0.4^{de}	9.7 ± 0.3^{d}	12.4 ± 0.6^{cde}
Hayanmi	2.5 ± 0.3^{cd}	3.3 ± 0.5^{de}	9.2 ± 0.5^{de}	11.8 ± 0.9^{def}
Happymi	2.7 ± 0.1^{c}	3.9 ± 0.4^{c}	7.2 ± 0.8^{f}	11.4 ± 0.4^{ef}
Healthymi	2.6 ± 0.6^{cd}	3.6 ± 0.4^{cde}	12.7 ± 0.8^{b}	15.8 ± 0.9^{a}
Pumpkin sweet potato	3.7 ± 0.3^{ab}	6.1 ± 0.3^{a}	9.9 ± 0.4^{d}	10.3 ± 0.3^{f}
Gold sweet potato	3.7 ± 0.3^{b}	6.0 ± 0.7^{a}	13.7 ± 0.1^{a}	15.4 ± 0.7^{a}


Gunmi
Gunpungmi
Daeyumi
Matnami
Borami
Shinyulmi
Swelling factor
temperature (^{o}C)
0 2 4 6 8 10 12 14 16 18
45 50 55 60 65 70 75 80 85


Jeonmi
Jeongmi
Hayanmi
Happymi
Healthymi
Pumpkin sweet potato
Swelling factor
temperature(°C)
temperature (°C)
0
2
4
6
8
10
12
14
16
18
45
50
55
60
65
70
75
80
85

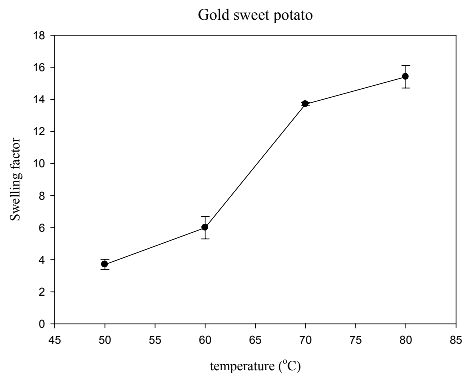


Fig. 4. Swelling factors of sweet potato starches

9. Digestibility

The *in vitro* digestibilities of sweet potato starches are in Table 10. In the present study, all sweet potato starches showed lower RDS in comparison to their SDS content which offers the advantage of a slow increase of postprandial blood glucose levels (Lehmann and Robin, 2007).

The SDS content, which is generally the most desirable form of dietary starch, followed the order: Gold sweet potao >Pumpkin sweet potato > Shinyulmi, Happymi > Gunpungmi > Jeonmi > Gunmi > Daeyumi > Borami > Hayanmi > Matnami > Healthymi > Jeungmi. It ranged from 30.9 to 53.0%, the highest being found in Gold sweet potato starch and lowest in Jeongmi starch. In particular, Gold sweet potato starch showed the highest contents of SDS, while Shinyulmi and Happymi had relatively high content of SDS among the Korean sweet potato starches. It might be related to the result that the SDS content was negatively correlated to Mw of amylopectin ($r=-0.53$, $p<0.01$). A similar inverse relationship between Mw of starch and digestibility had previously been reported in different legume starches (Sandhu and Lim, 2008). However, digestibility of native starches has been attributed to the interplay of many factors, including the botanical source (Goñi et al., 1997; Jenkins et al., 1984), physicochemical properties (Panlasigui et al., 1991), particle size (Snow and O'Dea, 1981), amylose/amylopectin ratio (Goddard et al., 1984), and the presence of lipid-amylose complexes (Goddard et al., 1984; Guraya et al., 1997). Although Jeongmi had the lowest SDS, it had the highest content of RS (62.8%) fraction. In this study, a positive correlation was observed between average size of granules and SDS+RS content ($r=0.50$, $p<0.01$). This entails that particle size is one of the important factors affecting the digestibility of starch. In addition, damaged starch content positively correlated ($r=0.65$, $p<0.01$) with rapidly digestible starch (RDS), and it showed that the extent of the damage in starch could affect the starch digestibility. Therefore, it was considered that these results might be affected to the highest RS content of Jeongmi starch.

Table 10. Relative amounts of RDS, SDS, and RS in sweet potato starches

Samples	RDS (%)	SDS (%)	RS (%)
Gunmi	10.6 ± 1.4[cde]	40.6± 0.8[d]	48.8 ± 1.3[d]
Gunpungmi	9.6 ± 0.7[de]	43.1 ± 0.6[c]	47.3 ± 1.2[def]
Daeyumi	17.4 ± 0.8[ab]	40.2 ± 0.8[d]	42.4 ± 1.4[g]
Matnami	10.6 ± 0.7[cde]	36.6 ± 1.8[e]	52.8 ± 1.1[c]
Borami	12.3 ± 2.0[c]	40.0 ± 0.9[d]	47.8 ± 2.0[de]
Shinyulmi	9.6 ± 0.6[e]	45.6 ± 0.3[b]	45.4 ± 0.9[ef]
Jeonmi	10.0 ± 1.2[de]	41.0 ± 1.6[d]	49.1 ± 0.5[d]
Jeongmi	6.3 ± 0.9[d]	30.9 ± 1.1[f]	62.8 ± 1.1[a]
Hayanmi	12.2 ± 0.9[c]	39.8 ± 0.7[d]	48.0 ± 1.4[d]
Happymi	18.6 ± 2.0[a]	45.6 ± 1.3[b]	35.7 ± 0.9[h]
Healthymi	12.5 ± 0.8[c]	31.4 ± 0.7[f]	56.1 ± 0.6[b]
Pumpkin sweet potato	12.7 ± 0.9[cd]	46.0 ± 1.8[bc]	41.3 ± 1.0[f]
Gold sweet potato	16.2 ± 1.3[b]	53.0 ± 1.6[a]	30.8 ± 2.8[i]

10. Pasting Properties

Pasting properties are among the important functional characteristics of starch in various foods and industrial applications. They affect starch-based product quality such as texture, stability, and digestibility (Brabet et al., 1997). RVA is mainly contributed by the swollen granules and breakdown of viscosity is caused by breakdown of gelatinized starch granules (Han and Hamaker, 2001). Differences in breakdown are related to differences in rigidity and fragility of the swollen granules.

Pasting parameters at 8% starch concentration for different sweetpotato starches varied (Table 11). For example, Happymi had the highest breakdown(645 cP) and relatively high peak viscosity (2469cP), whereas Borami had the lowest breakdown (316 cP) and peak viscosity (2294 cP). A positive correlation was observed between peak viscosity (PV) and breakdown (BD) (r = 0.71. p<0.01). This entails that starches which exhibit high PV are likely to have high BD values, leading to weak gels. Tsakama et al. (2010) suggested that starches which had high PV and BD could be used in the food industry, especially where low thickening power is needed such as in pastries. Breakdown is regarded as a measure of the degree of disintegration of granules or paste stability (Tsakama et al., 2010). At breakdown, swollen granules destroy further and amylose molecules generally leach into solution. It is a measure of cooked starch to withstand shear-induced disintegration.

P_{time} was negatively correlated with particle size (r = -0.43, $p < 0.01$), PV (r = -0.67, $p < 0.01$), and BD (r = -0.82, $p < 0.01$). It showed that starches with large granules underwent gelatinization relatively faster than those with smaller ones. Compared with other sweet potato starches (Tsakama et al., 2010), all sweet potato starches in this study had relatively low $P_{time.}$ Especially, Happymi had the lowest P_{time} (4.3min) among the Korean sweet potato starches.

In setback, indicating the retrogradation tendency, Shinyulmi had the highest value (1221cP) and Happymi had the lowest value (880cP).

The starch pasting properties are influenced by the interplay of the following factors: granule swelling, amylose leaching, starch crystallinity, and branch chain length distribution of amylopectin (Tester & Morrison, 1990; Hoover & Manuel, 199). Moreover, Jacobs et al. (1995) reported that both the formation of a tightly packed array of swollen and deformable granules and the leaching of amylose can contribute to viscosity development in starch paste during heating.

Table 11. Pasting properties of sweet potato starches from different cultivars

Samples	Peak viscosity (cP)	Breakdown (cP)	Final viscosity (cP)	Setback viscosity (cP)	Pasting time (min)	Pasting temperature (℃)
Gunmi	2541^{a}	435^{bcde}	3098^{a}	992^{abcd}	4.5^{bc}	74.8^{ab}
Gunpungmi	2576^{a}	579^{b}	3130^{a}	1133^{abc}	4.5^{bc}	75.1^{ab}
Daeyumi	2361^{abc}	406^{cde}	2893^{ab}	938^{cd}	4.9^{ab}	74.8^{ab}
Matnami	2202^{c}	334^{e}	2939^{ab}	1071^{abcd}	4.9^{ab}	76.0^{ab}
Borami	2294^{bc}	316^{e}	3073^{ab}	1099^{abcd}	5.0^{a}	74.8^{ab}
Shinyulmi	2543^{a}	543^{bc}	3222^{a}	1221^{a}	4.5^{bc}	75.1^{b}
Jeonmi	2426^{ab}	545^{bcd}	2863^{ab}	962^{bcd}	4.6^{abc}	75.4^{ab}
Jeongmi	2291^{bc}	422^{bcde}	2909^{ab}	1041^{abcd}	4.6^{bc}	76.7^{a}
Hayanmi	2288^{bc}	362^{de}	3129^{a}	1203^{ab}	4.7^{abc}	75.1^{ab}
Happymi	2469^{ab}	645^{a}	2704^{b}	880^{d}	4.3^{c}	74.3^{b}
Healthymi	2398^{abc}	561^{bc}	2847^{ab}	1009^{abcd}	4.5^{bc}	76.2^{ab}
Pumpkin sweet potato	2355^{abc}	403^{cde}	3120^{a}	1168^{abc}	4.5^{bc}	75.9^{ab}
Gold sweet potato	2279^{bc}	343^{e}	3048^{ab}	1112^{abcd}	4.9^{ab}	74.1^{b}

Table 12. Correlation coefficients between the physicochemical, digestion, pasting properties of sweet potato starches

Parameter[b]	AM	DS	PS	DP ≥37	Mn	Mw	Rz	Poly	RDS	SDS	RS	To	Tc	Tp	ΔH	AL	CP	PeakV	FinalV	BD	SB	Pasting temp.	Pasting time
AM	1																						
DS	-0.255	1																					
PS	0.556*	-0.495**	1																				
DP≥37	0.428	-.0302	0.490**	1																			
Mn	0.206	-0.259	0.187	-0.304	1																		
Mw	-0.179	-0.422**	0.071	-0.281	0.755**	1																	
Rz	-0.347	-0.479**	-0.223	-0.252	0.288	0.720**	1																
Poly	-0.452**	-0.371**	-0.120	0.025	-0.165	0.505**	0.728**	1															
RDS	-0.055	0.650**	-0.503**	-0.271	-0.367*	-0.426**	-0.218	-0.150	1														
SDS	0.301	0.038	-0.025	0.008	-0.344	-0.532**	-0.175	-0.251	0.426**	1													
RS	-0.194	-0.316*	0.241	0.062	0.415**	0.577*	0.226	0.250	-0.753**	-0.916**	1												
To	-0.262	-0.273	0.128	-0.247	0.308	0.292	0.195	-0.007	-0.659**	-0.226	0.456**	1											
Tc	-0.208	0.166	0.104	-0.127	-0.369*	0.291	-0.126	-0.103	-0.416**	-0.519**	0.562**	0.572**	1										
Tp	-0.322*	-0.108	0.029	-0.335*	0.402*	0.401*	0.176	0.028	-0.555**	-0.439**	0.565**	0.867**	0.797**	1									
ΔH	-0.177	-0.269	-0.183	-0.124	0.048	0.414**	0.621**	0.582**	0.122	-0.223	0.110	-0.388*	-0.484**	-0.323	1								
AL	0.320**	0.011	0.651	0.661**	-0.140	-0.224	-0.498**	-0.165	-0.292	-0.080	0.187	0.029	0.291	-0.027	-0.483**	1							
Cp	-0.109	-0.132	-0.033	0.009	-0.246	-0.105	0.179	0.132	-0.023	0.184	-0.125	0.039	-0.248	-0.102	0.032	-0.380*	1						
PeakV	0.291	0.057	0.276	-0.008	-0.056	-0.305	-0.332	-0.350*	-0.064	0.015	-0.089	0.179	-0.072	0.142	-0.213	0.151	-0.083	1					
FinalV	0.167	-0.279	0.147	0.356*	-0.254	-0.197	0.044	0.071	-0.225	0.185	-0.037	0.242	-0.150	0.046	-0.189	0.182	0.063	0.362*	1				
BD	0.174	0.181	0.176	-0.364*	0.196	-0.061	-0.319*	-0.343*	0.019	0.015	-0.020	0.081	0.079	0.196	-0.132	-0.077	-0.195	0.705**	-0.272	1			
SB	0.104	-0.322*	0.091	0.225	-0.154	-0.037	0.131	0.168	-0.259	0.129	0.019	0.255	-0.084	0.098	-0.181	0.050	0.010	0.136	0.903**	-0.259	1		
Pasting temp.	-0.039	-0.171	0.149	-0.047	0.363	0.450**	0.211	0.097	-0.412**	-0.512**	0.555**	0.277	0.370*	0.351*	0.010	0.049	-0.047	-0.097	0.103	0.009	0.265	1	
Pasting time	-0.298	0.073	-0.433**	0.128	-0.217	-0.024	0.232	0.263	0.143	0.055	-0.102	-0.096	0.057	-0.117	0.082	-0.108	0.219	-0.672**	0.014	-0.824**	-0.011	-0.217	1

[a] Significance level: *, ** and *** = $P<$ 0.05, 0.01 and 0.001, respectively.

[b] Parameters, AM = amylose content; DS = damaged starch; PS = particle size; Poly = polydispersity; AL = amylose leaching, CP = close packing; V = peak, final viscosities in RVA; BD = breakdown; SB = setback

CONCLUSION

This research was carried out to elucidate the physicochemical, pasting, digestion properties of 11 Korean sweet potato starches which were cultivated by National Institute of Crop Science, Rural Development Administration of Korean government in Korea. Variations in some physicochemical properties of starches from 11 Korean sweetpotao were observed, indicating that they might be suitable for diverse food applications. Some sweet potato starches represented unique characteristics, and could further be studied on relationship between their characteristics and genetic resource or growing conditions of them. Amylose content was 12.5-17.4%, and a similar chain length distributions of amylopectin was observed in sweet potato starches. Jeongmi starch had the highest values for Mw of amylopectin, while Daeyumi starch had the lowest values. All sweet potato starches showed a characteristic C_a type X-ray diffraction patterns. Thermal properties of DSC showed high values of T_o, T_p, and T_c in Jeongmi, but the low value in Happymi. Pasting properties of RVA showed the lowest values of pasting temperature and setback viscosity in Happymi, but the highest values in Jeongmi starch. Happymi had not only a high breakdown value but also high peak viscosity and final viscosity. In digestion properties, Jeongmi had the highest RS, and Shinyulmi and Happymi had high SDS contents. These low digestible sweet potato starches could be used in foods for diabetic patients. The current study may stimulate further interest in the use of Korean sweet potato starches in the food industry. It is desirable that further studies be performed on utilization of Korean sweet potato starches in common food products like snack foods and starch noodles.

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국문 초록

지금까지 국내에서 식용, 가공용 고구마뿐만 아니라 안토시아닌이 다량 함유된 자색고구마와 베타카로틴이 풍부한 주황색 고구마 등 다양한 품종이 개발되었다. 고구마 전분에 대한 여러 연구가 진행되어 있지만, 농촌진흥청 국립식량과학원에서 제안한 주요 장려 품종 고구마 전분에 대한 연구는 아직 미흡하다. 그리하여 국내에서 육성된 11가지 고구마 전분에 대한 이화학 및 호화적 특성과 소화율을 조사하여 식품 산업의 새로운 식품 소재로서의 사용 가능성을 알아보고자 하였다.

고구마 전분 입자는 원형, 타원형, 다각형, 종모양 등 다양하였으며 입자 크기 범위는 3.7-37.5㎛로 증미가 가장 큰 평균입도를 보였고 보라미가 가장 작은 평균입도를 보였다. 아밀로오스 함량은 12.5-17.4% 로 전미가 가장 높았다. 아밀로펙틴 분자량은 증미가 14.6×10^{7}g/mol 로 가장 컸고, 대유미가 7.2×10^{7}g/mol 로 가장 작았다. 아밀로펙틴의 구조를 분석한 결과 가지 사슬 분포는 품종별로 유사하였고, DP≥37 의 분포도와 아밀로오스 침출 정도가 양의 상관관계임을 확인하였다. X선 회설 유형은 모든 품종에서 C_a

형을 보였다. 시차주사열량계로 열역학적 특성을 조사하였을 때, 신율미와 증미의 호화개시온도, 호화피크온도, 호화종결온도가 높았고 해피미는 다소 낮은 값을 나타내었다. 또한 보라미의 호화엔탈피가 가장 높았다. 11가지 고구마 전분의 온도에 따른 팽윤력은 품종에 따라 독특한 변화 양상을 보였다. 페이스트 특성을 측정한 결과, 해피미는 낮은 호화온도 및 호화시간, 그리고 낮은 치반점도를 나타내었고, 높은 강하점도, 피크점도, 최종점도를 보였다. 소화적 특성으로는 난소화성 전분 함량은 증미 (62.8%)가 가장 많았고, 지소화성 전분 함량은 신율미 (45.6%)와 해피미 (45.6%)가 가장 높았다.

결론적으로, 지소화성 전분의 함량이 높은 고구마는 혈당 조절용 식품 소재로 이용할 수 있으며 가공 식품에 따라 그 페이스트 특성에 맞는 고구마 전분을 선택하여 사용할 수 있을 것이다.

이 연구는 농촌진흥청 국립식량과학원에서 육종한 주요 품종의 고구마에 대한 이화학 및 호화적 특성과 소화율을 구명함으로써 식품산업에서 국내 고구마의 소비를 증대시킬 수 있는 방안을 모색하기 위한 기초자료를 제공하였다.

주요어: 한국산 고구마, 고구마 전분, 이화학적 특성, 지소화성 전분, 페이스트 특성

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